DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE
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Spring Term 2007
6.101 Introductory Analog Electronics Laboratory
Laboratory No. 4

READING ASSIGNMENT

In this laboratory, you will investigate the performance of operational amplifiers in simple circuit configurations. We will discuss various aspects of operational amplifier behavior in class. In addition, you should have read at least the ***Operational Amplifiers*** class reading assignments in the class outline under section 7.

Objective: At last! The Bigtime!! Op-amps!!! You will be using the LM741, which is one of the earliest of popular operational amplifiers, the LF356 which is a precision JFET-input op-amp with very low input bias current, wider open-loop bandwidth, higher slew rate, etc., the LT 1632C, a dual rail-to-rail op-amp, and the LT1011A comparator.

Acknowledgement: I would like to thank National Semiconductor Corporation for their generous donation of all of the integrated circuits used in this laboratory, with the exception of the LT1011 and the LT1632C devices, which were generously donated by Linear Technology, Inc.

Experiment 1: The Inverting Configuration.

In this experiment, you will be connecting a LM741 in the inverting configuration of Figure 1. You will learn to adjust the offset of the amplifier, measure its bandwidth and see how its performance is limited by its slew rate.

1. Construct the circuit of Figure 1. [Refer to the LM741 data sheet to make sure that you connect to the proper pins of your LM741]. Choose resistor values $R_1 = R_2 = 15\ k\Omega$ and $R_3 = 7.5\ k\Omega$ and do not install the 10 kΩ potentiometer at this point. Ground the input v_{in} and measure the output voltage [it will probably differ by some number of millivolts from zero]. This voltage is caused by the ***input offset*** *voltage* that can be modeled as a dc voltage source in series with the ***non-inverting input*** to the amplifier and the gain of the amplifier [in this case the gain is two for a voltage applied to the non-inverting input]. Calculate the corresponding input offset voltage and compare this value with that found on the LM741 data sheet.

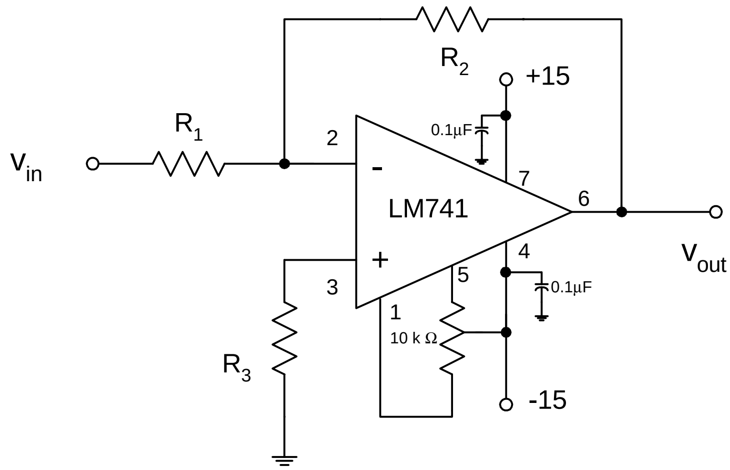


Figure 1: Circuit for experiment 1.

2. Now install the 10 kΩ offset-null potentiometer. Depending on the style of the potentiometer, you may have to solder some leads onto it so that you can plug it into your protoboard. [Soldering irons are installed near the 6.071 lab area, and solder and other tools are available from the instrument room window.] Adjust the potentiometer to zero the output voltage**.**

Q 1.1 What range of output-offset voltage can be achieved by adjusting the potentiometer over its entire range?

3. Now connect the signal generator to the input and adjust it to produce a 0.2 Vp-p, 1 kHz sinusoid. [Remember that your function generator source impedance is default calibrated for a 50 Ω load. Be sure to switch it to ***High Z.]*** Measure the magnitude of the voltage gain of this connection.

Q 1.2 Do you need an input coupling capacitor between the function generator and R_1? Why or why not?

4. Increase the frequency of the signal generator until the amplitude of the output voltage begins to decrease. Find the frequency at which the amplifier gain is $1/\sqrt{2}$ of its low-frequency [1 kHz] value. This frequency can be considered to be the bandwidth [-3dB point] of this particular configuration. Measure the phase-shift between the input and output voltages at this frequency. [See the attached instructions for measuring phase-shift with the Tektronix 2445 oscilloscope, the Tektronix 34XX series have a phase measurement available under the "measurements" menu.]

5. Now change the feedback resistor R_2 to 150 kΩ, calculate a new value for R_3, and repeat parts 2, 3 and 4.

If you disconnect the offset potentiometer, you will notice that the output offset is approximately 5.5 times larger than that found when the amplifier was configured for a gain of 1 from the inverting input.

Q 1.3 Why?

Q 1.4 Why did we change R_3.?

Q 1.5 What is the ideal value of R_3 relative to the values of R_1 and R_2?

- Notice that while the inverting amplifier gain is a factor of 10 larger than that of the first configuration, the bandwidth is approximately a factor of 5.5 lower. If you were to examine this configuration for other values of gain, you would find out that the higher the gain, the lower the bandwidth; specifically, that the product of (one plus the gain) times the bandwidth is a constant.

6. With the signal generator set to the bandwidth frequency [-3dB point] for the gain of -10, which you found in part 5, increase the amplitude of the input voltage until the output voltage begins to distort [i.e. it will no longer look sinusoidal, but more like a triangle wave]. At this point, the amplifier has reached its ***slew-rate*** limit.

The slew-rate limit of an operational amplifier is caused by a current source within the amplifier [biasing the first stage, the input differential stage, of the amplifier] that limits the amount of current that can be supplied by the first stage of the amplifier. When the amplifier is pushed to the point that this limit is reached, it can no longer function properly. The slew-rate limit manifests itself as a maximum value of dv_{out}/dt for the amplifier because there is an internal amplifier capacitance that must be charged by the first-stage output current and a first-stage current limit thus corresponds to a maximum dv/dt for this capacitor.

With the input amplitude set to the value at which the output voltage just starts to distort, calculate the maximum value of dv_{out}/dt on the output voltage.
Q 1.6 How does this value compare with the slew-rate value that is found in the LM741 spec sheet?

7. Reduce the frequency of the input voltage by a factor of 5 and again measure the slew rate of the amplifier by finding the value of dv_{out}/dt for which the output voltage begins to distort. Compare this to the earlier measurement of slew rate.

8. With the signal generator set to a frequency of 1 kHz, increase the amplitude of the input voltage until the output voltage saturates [the top of the sine wave just begins to flatten]. Measure the saturation voltage of the amplifier [both positive and negative] and compare these values with the magnitudes of the positive and negative supply voltage. Repeat this measurement using a load resistor of 510 ohms connected between output and ground.
Q 1.7 How do the saturation voltages with the load resistor differ from the test using the amplifier without a load resistance [infinite load impedance]?

9. Set the signal generator to produce a square wave input voltage. Adjust the amplitude and frequency of the input voltage until the output becomes a triangular wave.
Q 1.8 Why is the output waveform not a square wave?
Calculate the dv/dt for this triangular wave. [Note that this is a much easier and more accurate way to measure the slew rate of your LM741.]

10. Now replace the LM741 chip with an LT1632C Dual Rail-to-Rail op-amp. [Note: this device was not given out in the brown envelope with your other IC's when you got your lab kit. These devices are in a drawer on the windowsill of building 38, on the 6th floor.]

WARNING: This device contains TWO op-amps. Please connect the output terminal to the inverting (–) input of the unused op-amp, and ground the non-inverting (+) input to prevent it from oscillating while you are working with the other op-amp.

Repeat the measurement of saturation voltage in step 8 above.
Q 1.9 How does the saturation voltage at the output of this device differ from the saturation voltages obtained in step 8?

<u>Experiment 2: Comparing the LF356 and the LM741 operational amplifiers.</u>

In this experiment, you will compare the performance of the LF356 operational amplifier to that of the LM741. Note that the LF356 has basically the same pin connections as the LM741. However, the spec sheet shows a 25 kΩ offset-null potentiometer with its wiper connected to the positive supply voltage. Connect an LF356 in the configuration of Figure 1. Do not install an offset-null potentiometer [it is not necessary for the purposes of this experiment].

1. **Q 2.1 With the same resistor values you used for page 2, item 5, and a 0.2 $V_{p\text{-}p}$ sinusoid input, how does the bandwidth of the amplifier built with an LF356 compare with that which you measured in the corresponding configuration using the LM741 op amp? Compare your measurement with the value given in the spec sheet.**

2. Measure the slew rate of the LF356. You may find it difficult to make an accurate measurement; make an educated guess.
Q 2.2 How does the measured slew rate of the LF 356 compare with the value found in the spec sheet? How does the slew rate compare with the LM 741 slew rate?

<u>Experiment 3: Common amplifier configurations.</u>

In the previous experiments, you examined the inverting op-amp configuration. In this experiment, you will examine other common configurations. These circuits are shown in Figure 2. Use a LM741 op amp for these experiments, ***except use the LT1011A comparator for figure 2c, the comparator circuit.*** For each circuit, draw a schematic and label all values in your lab report.

1. Figure 2[a] shows the configuration of an inverting adder. Select the resistor values such that $v_{out} = -(1.5v_{in1} + 3\ v_{in2})$. Select the value of resistor R_4 to minimize the effects of input bias current. Build the circuit and confirm its performance by applying DC voltages to each input. One voltage can be the +5 V DC supply, the other can come from your function generator offset voltage [turn off the AC output]. Be sure not to drive your output into saturation with large input voltages.

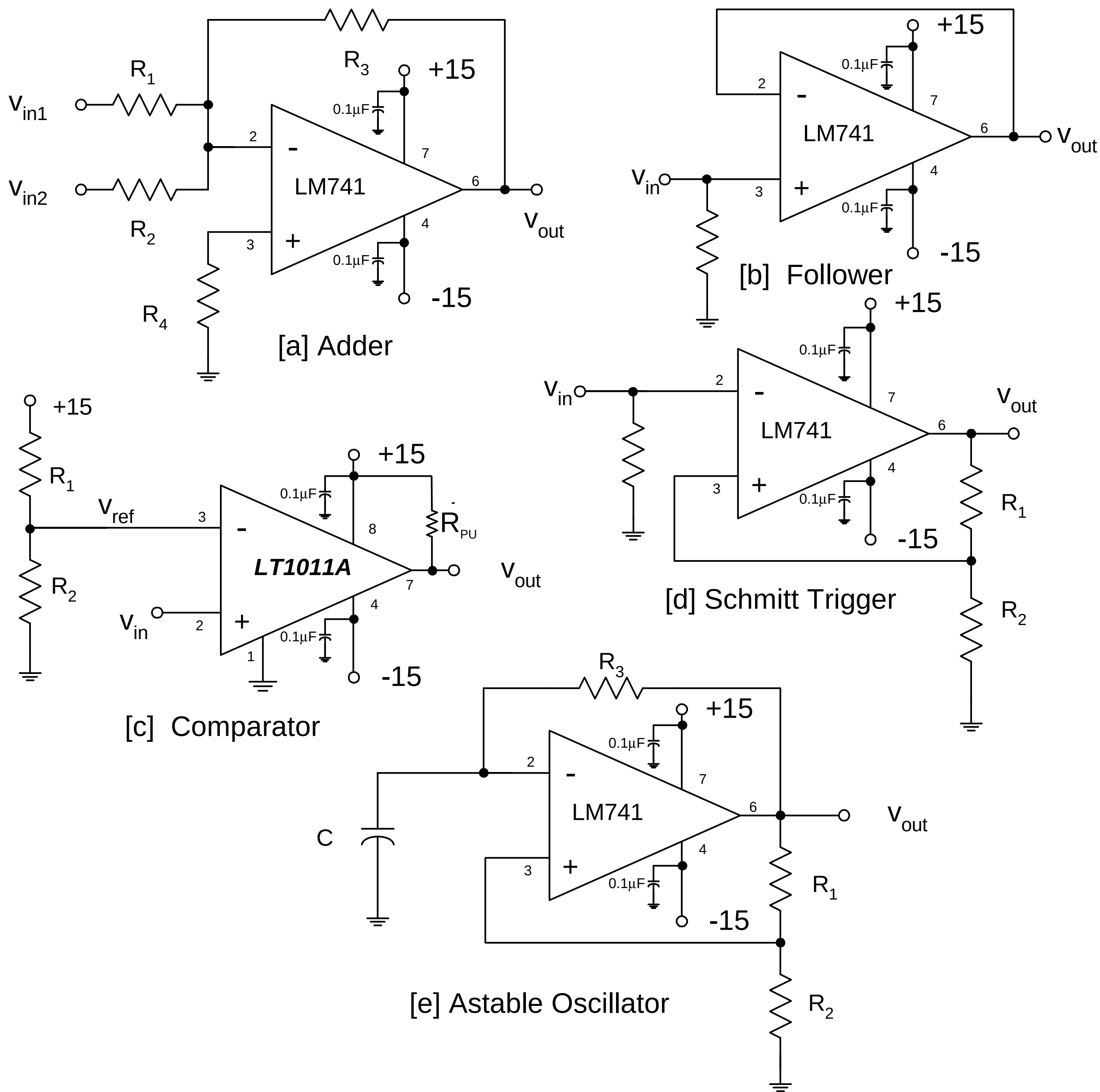


Figure 2: Circuits for experiment 3.

2. Construct the voltage follower [unity-gain buffer] of Figure 2[b]. Omit the resistor to ground.
   Q 3.1 If you do not use a coupling capacitor, the circuit should work properly. Why?

- Find the frequency at which the gain drops to $1/\sqrt{2}$ [-3dB] of the low-frequency value.

Insert a 10 MΩ resistor in series with the input of the voltage follower [to simulate a voltage source with a high source impedance]. Recognizing that a key feature of the voltage follower is its high input impedance, one would expect that there would be no change in the gain of the follower circuit.

Q 3.2 Your scope probe has a resistance from tip to ground of 10 MΩ. What effect will your scope probe have if you use it to measure the input voltage to this amplifier?

You will observe that this is in fact true at low frequencies. However, you will notice that the gain drops off fairly rapidly with frequency. This is due to the presence of parasitic capacitance in the circuit. In this case, the high impedance of the source resistance in combination with a small amount of capacitance between the input to the op-amp and ground forms an RC filter that reduces the gain of the op-amp. Measure the frequency at which the amplifier gain drops to $1/\sqrt{2}$ [-3dB] of the low-frequency value in this configuration and use this measurement to estimate the value of the parasitic capacitance. ***Note that the effects of stray capacitances [along with issues such as input bias current] limit the magnitude of resistance values that can be used in practical operational amplifier circuit configurations.***

3. Figure 2[c] shows the circuit configuration for a comparator. Resistors R_1 and R_2 set the voltage level at which the circuit output will switch between positive and negative saturation. Due to the internal capacitor required to stabilize IC's designed for negative-feedback amplifier operation, and the nature of the output stage, driving such an amplifier into saturation can require a long time for it to recover once the input stimulus changes. This makes the op-amp a pretty bad choice for use as a comparator at higher frequencies. [Comparators are usually operated without feedback.] Thus, a series of products specifically designed for use as comparators has been developed. These devices have open collector outputs and thus require an external resistor connected to the positive supply rail in order to operate properly. The size of the external resistor will depend on the amount of current needed to drive the load when the output transistor is "on" [saturated] and current flows from the positive supply through the load resistor to the load on the output. Typical resistor values are in the 1.0kΩ to 10kΩ range. *This resistor is labeled R_{PU} in the schematic.* Also please note that even though the comparator is connected to both the +15 v and –15v supplies, the output swings only from ground to +15 volts in the circuit shown. [The output can be arranged to drive loads referred to the positive supply or the negative supply, as well as a load referred to ground as illustrated here. See the LT 1011A spec sheet for more info on the use of this device. If your comparator oscillates at the transition (from low to high or high to low) point, see the spec sheet application hints for ways to cure this.]

- Construct a comparator that switches when the input voltage reaches a level of approximately +5.0 V. ***Use standard 5% resistor values,*** 1 each for R_1 and R_2.

- Measure the time that it takes the comparator to switch between the positive and negative [high and low] saturation voltages.

4. Figure 2[d] shows the circuit configuration for a Schmitt trigger. A Schmitt trigger uses the operational amplifier [good for low frequencies only!] as a comparator along with positive feedback to create a "hysteretic" switch. If you analyze this circuit, you will find that if the output of the Schmitt trigger is positive, the input will have to be raised to some fraction of the output voltage before the output will switch to a negative value. It will then require the same level of negative input voltage before the output will switch positive. This circuit can be used to "compare" noisy signals that are expected to have enough difference in their values to exceed the design thresholds. In other words, the Schmitt trigger will not switch output states when only noise is presented to the input, if the noise is lower than the thresholds. The standard comparator in figure 2[c] above will change state easily [and often!] with a noisy input. Find R_1

and R_2 such that the threshold-voltage of the Schmitt trigger is approximately 1/3 the magnitude of the supply voltage. Construct the circuit and verify your calculation.

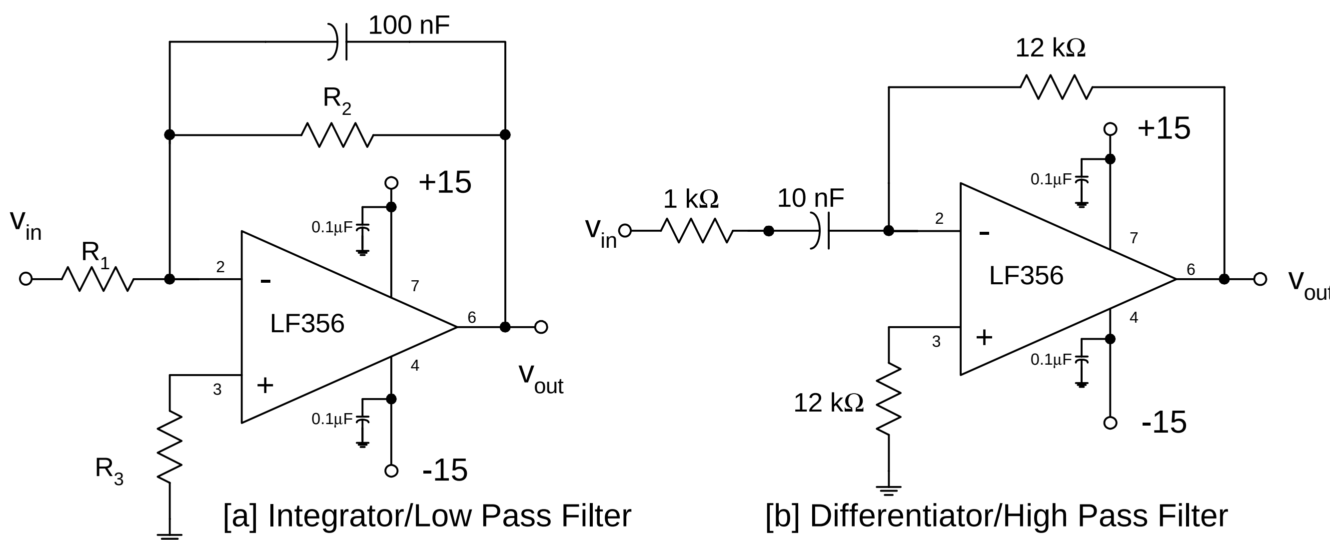
5. In Figure 2[e] a capacitor and resistor have been added to the Schmitt trigger of Figure 2[d] to produce an oscillator. Show the output waveform in your lab report; also show the capacitor charging and discharging voltage.

Q 3.3 How does the value of the hysteresis threshold voltage affect the frequency of oscillation?

Find values of R_3 and C to produce an oscillation at approximately 1000 Hz. Measure the actual frequency using your scope or your DMM.

Experiment 4: Integrators, filters, etc.

In this experiment you will use capacitors as well as resistors in the feedback circuits of your operational amplifier. All of these circuits can be thought of either in time domain terms [differential equations] or frequency domain terms [transfer functions], depending upon the application.



[a] Integrator/Low Pass Filter [b] Differentiator/High Pass Filter

Figure 3: Circuits for experiment 4.

1. Figure 3[a] shows the configuration of a low-pass filter/integrator. In the frequency domain, this circuit corresponds to a low-pass filter. For this experiment, you wish to design this circuit to be an integrator at a frequency of 10,000 Hz. Because this will not be a perfect integrator, you will want to make sure that the phase-shift between the output and the input will at least be -85^o [an ideal integrator would have a phase-shift of -90^o]. Design the circuit to have a low-frequency gain of –10. Show your calculations. Measure the magnitude and phase angle of the circuit transfer function at 10,000 Hz to verify your calculations.

[**NOTE:** In order for the integrator to be integrating at 10,000 Hz, you must be well down on the slope of the response plot caused by the pole determined by R_2 and the 100 nF capacitor in the feedback loop. It is best to keep a one-decade difference between the corner frequency and the frequency where you want the integrator to work. Remember, that while we draw straight lines to show gain at the corner frequencies or break points, the actual response change is gradual, and this break point is only -3dB, which corresponds to a phase shift of only -45 degrees. So please choose your -3dB point with this in mind.]

- Plot the measured magnitude of the transfer function as a function of frequency. On the same plot, draw the asymptotes for this transfer function that you would expect based upon the calculated transfer function.
  Q 4.1 What is the bandwidth of this filter?

2. Figure 3[b] shows the circuit configuration for a differentiator. In the frequency domain, this circuit corresponds to a high-pass filter.

- Calculate the transfer function for this circuit.
  Q 4.2 For what frequencies does this produce an output waveform that is the derivative of the input?

- Apply a triangular wave to this circuit. Observe the output as a function of frequency. Verify that this circuit does indeed operate as a differentiator. Notice that at higher frequencies you will see that the slew-rate limit of the amplifier dominates the circuit performance as the input amplitude is increased.
  Q 4.3 At what frequency does the performance of your differentiator begin to deteriorate?

- In the frequency domain, this circuit can be thought of a high-pass filter. Plot its measured sine-wave frequency response from 10 Hz to 100 kHz. On the same plot, draw the asymptotes for this transfer function that you would expect based upon the calculated transfer function.

<u>Experiment 5: A few other op-amp applications.</u>

1. Construct the circuit of Figure 4[a]. With the function generator set to produce a 5 V p-p sinusoid at 60 Hz, observe and sketch the output waveform. Notice that it is a half-wave rectified version of the input voltage but that you do not see the 0.6 V drop that you would expect to see if you had made a simple diode rectifier. This circuit is known as a precision rectifier. [The diode is enclosed in the feedback loop, and thus feedback corrects for the diode forward voltage drop “error”.]

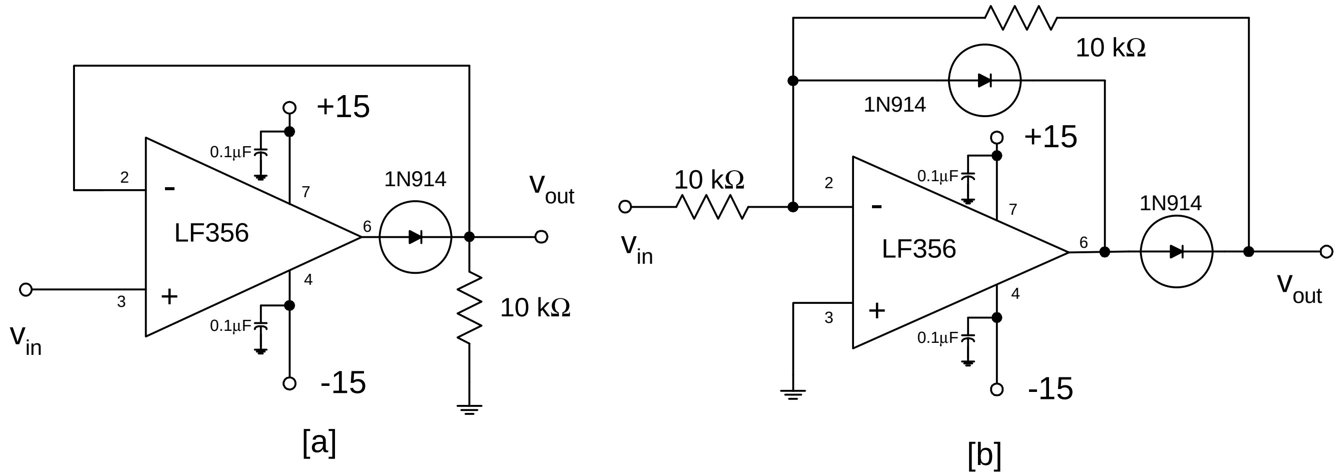


Figure 4: Circuits for experiment 5.

Increase the frequency until the output voltage no longer looks like a nicely rectified sinusoid. The reason for this can be seen if you look at the amplifier output, pin 6. Notice that when the input signal is negative, the diode is off, switching off the amplifier feedback and causing the amplifier output to go all the way to negative saturation. When the input voltage again becomes positive, it takes a finite amount of time [determined by the amplifier slew rate] for the amplifier output to return from negative saturation and to catch up with the input. Measure the recovery time of this circuit.

Figure 4[b] is a circuit for an “improved” precision rectifier. Construct this circuit and verify that it indeed provides improved performance over the circuit of Figure 4[a]. Increase the input frequency until you observe that the performance of this rectifier circuit begins to deteriorate. **Q 5.1 Approximately at what frequency does this occur? Why does this circuit perform better than the simple rectifier?**

2. As indicated in the data sheet, the LF356 op amp can supply a maximum output current of approximately 25 mA [the LF356 is short-circuit protected to limit its output current to a value that will not destroy the device]. Figures 5[a] and [b] show two circuit configurations in which a push-pull output stage [consisting of a 2N3904 and a 2N3906 transistor] has been added to the output of the LF356. According to the data sheets, each of these transistors can supply up to 200 mA and can dissipate a total power of up to 350 mW.

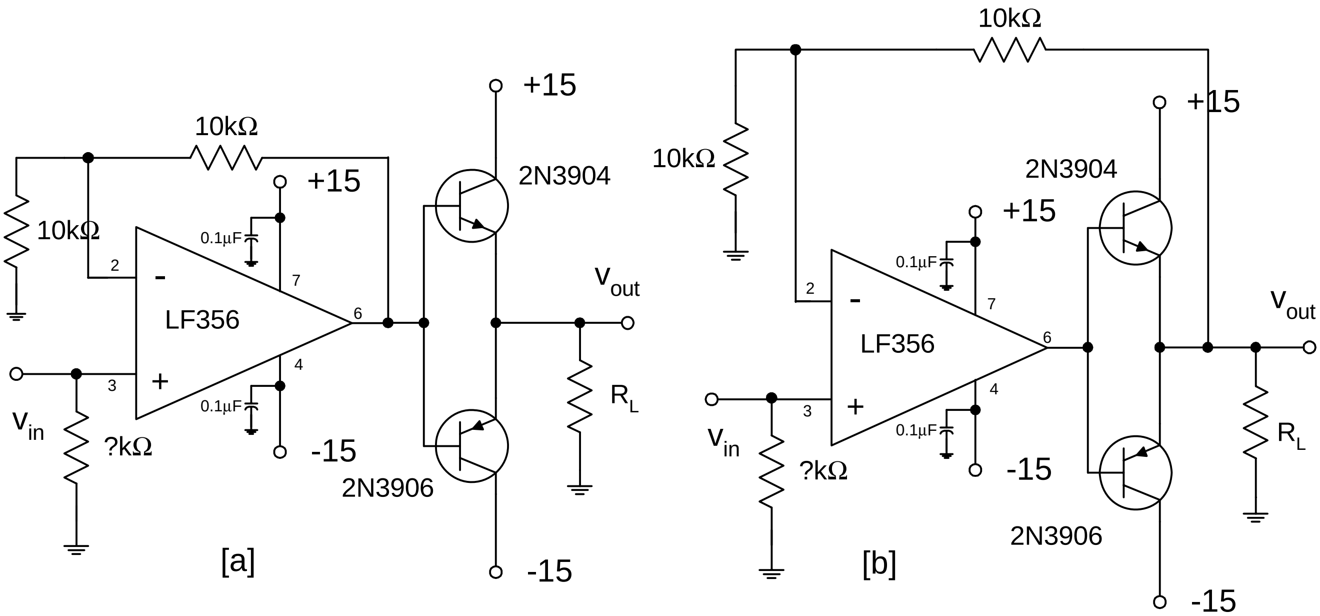


Figure 5: Push-pull output stage circuits.

With R_L = 2.2 kΩ, apply a 500 mV p-p, 500 Hz sinewave to the input of each circuit. **Q 5.2 What output voltage do you see from each of these circuits? Why?**
Q 5.3 How does the feedback used in the circuit of Figure 5[b] help this circuit to work? [Hint: Look at and compare the outputs of the operational amplifiers in each of the circuits.]

Increase the input amplitude to 1.0 V p-p. Again compare the two output waveforms. Notice the distortion [known as crossover distortion] on the output of the circuit of Figure 5[a]. **Q 5.4 What is the source of this distortion?**
Q 5.5 How does the configuration of Figure 5[b] greatly reduce the level of this distortion?

- **Q 5.6 What is the minimum value of load resistor R_L that can be used in the circuit of Figure 5[b] without exceeding the power dissipation capabilities of the output transistors?** [To avoid damage to the transistors, it is a good idea to limit the power dissipation in these transistors to a maximum of 200 mW.] Use this value of load resistor and verify that the circuit can indeed drive this load resistor through the complete range of the supply voltage. [Hint: You may have to use 10 nF or 100 nF bypass capacitors between the op-amp plus and minus supplies and ground to keep your circuit from oscillating for this test.] Now remove the push-pull output stage and drive the load resistor directly from the LF356 [connected as a voltage follower].
  Q 5.7 What is the maximum voltage and current that the op amp can supply to this load? Find this value on the op-amp spec sheet.

- Replace the LF356 in figure 5b with one of the op-amps in the LT1632C. Repeat all the instructions in the paragraph above using this new device.
  Q 5.8 What are the major differences?